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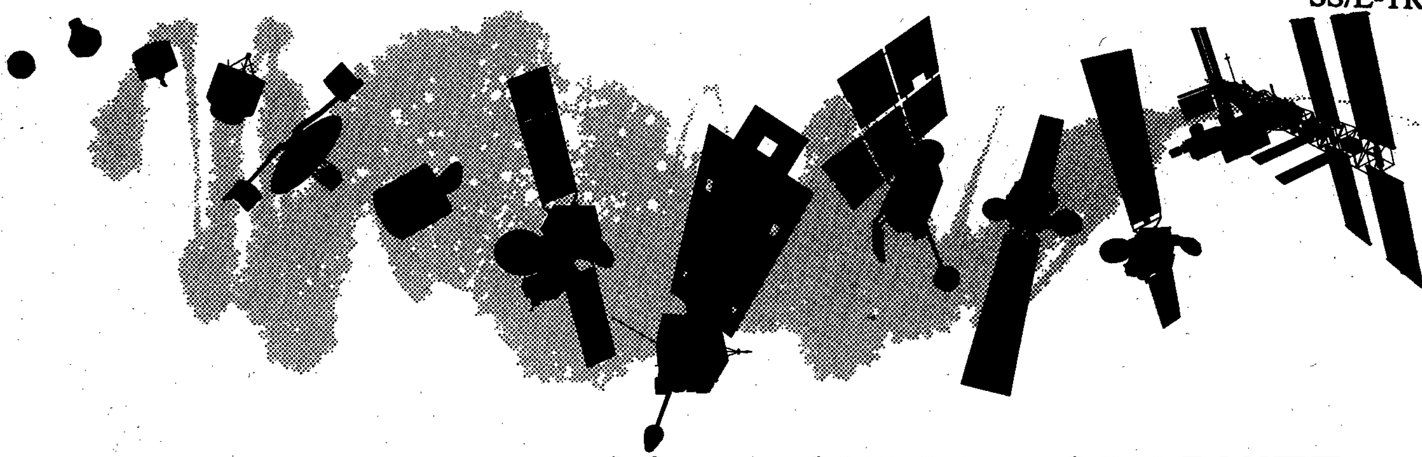

HIGH THERMAL CONDUCTIVITY GRAPHITE ELECTRONIC COMPONENTS

First Quarterly Progress Report
May - July 1996

SPACE SYSTEMS/LORAL

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Mr. Ingham Mack
Office of Naval Research
Code 312
Room 607
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217-5660

Prime Contractor:

Space Systems/Loral
3825 Fabian Way
Palo Alto, CA 94303-4604

Principal Investigator:

Dr. S. O. Peck
Space Systems/Loral
3825 Fabian Way
Palo Alto, CA 94303-4604

Contributing Authors:

Dr. G. L. Young
Mr. W. J. Mellberg
Mr. A. F. Wellman
Mr. J. E. Cooney
Mr. B. G. Robins

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CONTENTS

SUMMARY

This project will apply high thermal conductivity graphite to three major spacecraft electronic components: (1) the thermal plane of a printed wiring board, (2) the subassembly or tray that holds the board, and (3) the equipment panel that the tray mounts on. The complete heat transfer path from chip level heat source to radiative rejection on the exterior surface of the equipment panel will therefore be addressed. Thermal and structural requirements representative of current spacecraft will drive an optimized solution strategy. The project will be completed by fabricating the three prototypical test articles and measuring their performance in a representative space environment.

TASK 1: THERMAL PLANES

SPACECRAFT ELECTRONIC APPLICATIONS

The serial bus I/O module (SIAM), of which there are now 40 + 4 modules (two types) per spacecraft, is jeopardizing the overall spacecraft electronics mass budget. Due to the large number of repeat units, high power densities, and mass problems, the SIAM is an ideal target for thermal plane and tray development work. The Motor Power Switch (MPS) is a another candidate since it is a large format board and currently the hottest board on the spacecraft. The SIAM board and tray and MPS board and tray are shown in Figures 1 and 2, respectively. The performance of the thermal planes and trays developed under this contract will be assessed using chip power densities derived from these boards.

The SS/L timeline for the development and incorporation of chip-on-board technologies is three to five years from now. Therefore, we will continue to pursue an aggregate printed wiring board/thermal plane CTE of 6 ppm/K in order to match that of our current chip packages. It is worth noting that the current BeO thermal plane and PWB have an aggregate CTE of 8 ppm/K. That is, a 2 ppm/K mismatch is acceptable as far as the chip packages are concerned. The issue for graphite based thermal management products is that CTE can be quite low, and strategies for either increasing the CTE of the aggregate system, or accommodating the CTE mismatch, will have to be developed.

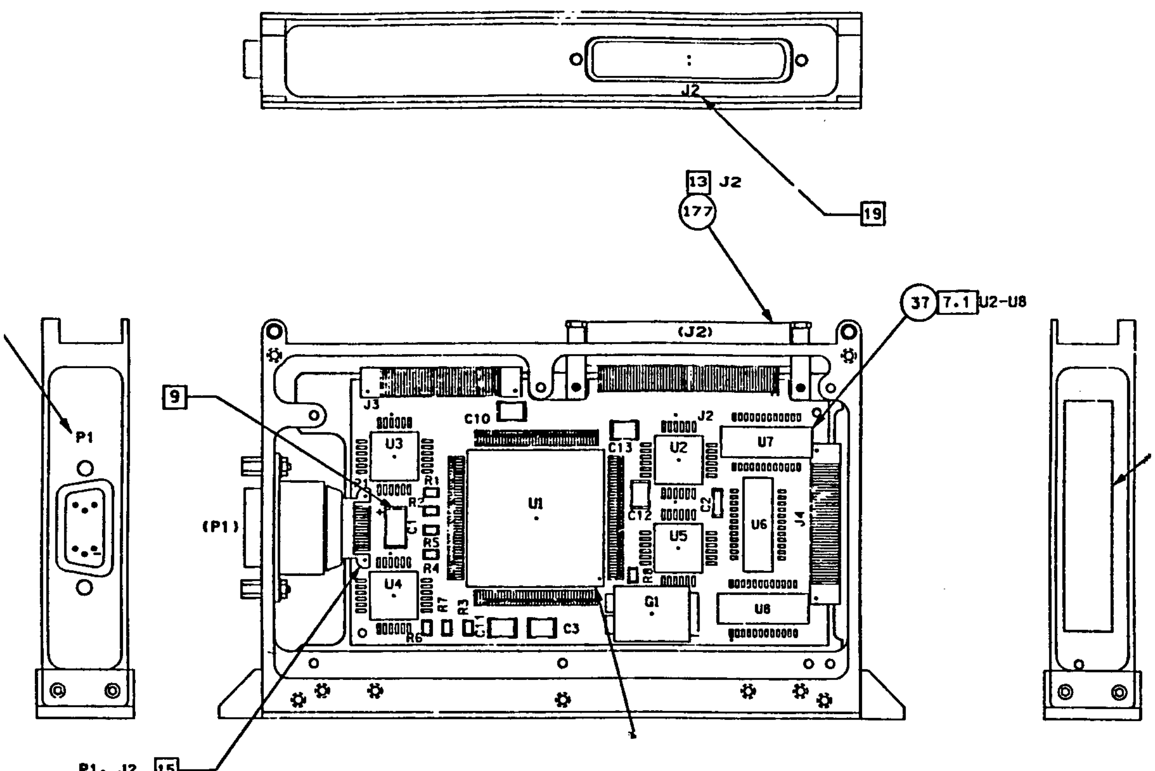

Figure 1. SIAM Board and Tray

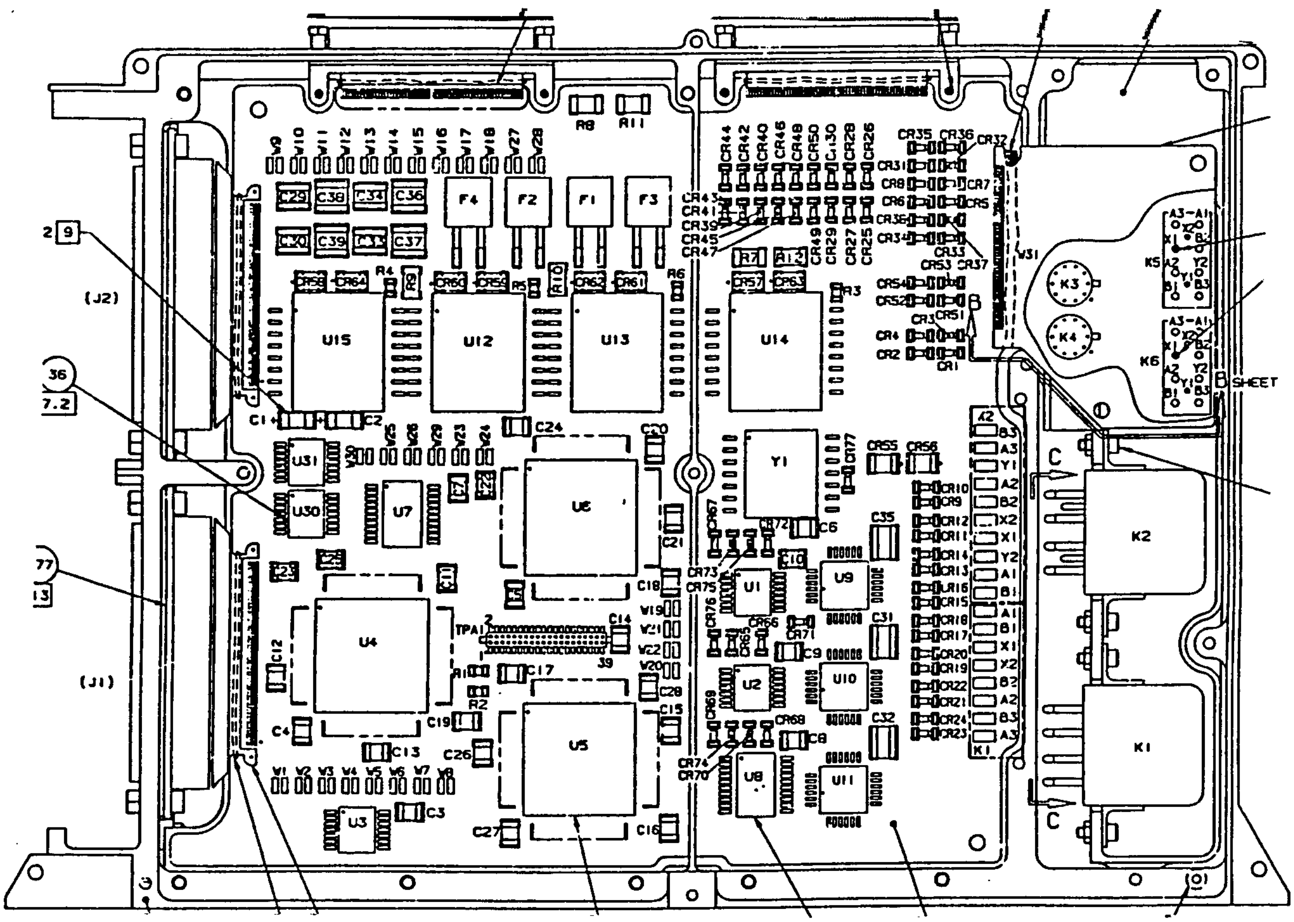

Figure 2 Motor Power Switch Board and Tray

REQUIREMENTS DEFINITION

The performance criteria for thermal planes include CTE, ΔT, in-plane conductivity, through thickness conductivity, stiffness, cost, and mass. The current BeO design serves as a baseline. However, it is not clear how to rank these relative to one another. For example, aggregate thermal plane/wiring board CTE should be no higher than the current CTE of 9 ppm/K (to avoid solder pin failure) and no lower than 6 ppm/K (to avoid high thermal stresses within the boards). Any value within that range is probably acceptable. The maximum chip junction temperature can be no higher than 110 °C. Reducing the overall board operating temperature is probably more desirable than reducing mass. Cost is important, but last on this list. The current BeO properties, and quasi-isotropic K1100 for comparison, are shown below.

Table 1 K1100 - BeO Comparison

Property	K1100 Quasi-Isotropic	BeO (E-60)
Tensile Modulus (Msi)	40.0	46.0
Thermal Conductivity (W/m-K)	249.	225.
Thermal Expansion (ppm/K)	-1.0	6.1
Laminate Density (g/m^3)	1.80	2.30

CANDIDATE MATERIALS

The candidate materials for the thermal plane were reviewed. K1100 prepreg, ThermalGraph panel, K1100 based carbon/carbon, and TC1050 encapsulated pyrolytic graphite were chosen for evaluation. Table 2 lists the candidate fibers and relevant material properties. It is difficult, however, to present a head-to-head comparison of these materials due to differences in matrix materials, layup, and processing. For example, the properties in Table 2 are that of K1100 fiber, ThermalGraph 8000 without an infiltrated resin, carbon/carbon in a four-to-one layup, and estimated properties for a fiber form of TC1050. A tabulation of fiber/matrix systems reviewed and their properties are listed in Appendix A.

Table 2 Thermal Plane Candidate Materials

Property	K1100	Thermal Graph 8000 Panel	K1100 C/C 4:1	Advanced Ceramics TC1050
Long. Thermal Cond. (W/m-K)	950-1170	700[1]	453	1180
Tran. Thermal Cond.(W/m-K)		20	153	1180
Electrical Resistivity (μΩ–m)	1.1-1.3			na
Longitudinal CTE (ppm/K)	-1.6	-0.5	-1.5 to -0.5	~fiber
Transverse CTE(ppm/K)	na	8-10	5 to 7	~fiber
Fiber Tensile Strength (ksi)	350-550		55	~fiber
Fiber Tensile Modulus (Msi)	130-145	50[2]	47	~fiber
Fiber Density (g/m^3)	2.15-2.25	2.20	1.85	2.13

The following points are relevant to the thermal plane material candidates:

- K1100/cyanate ester is probably not a good choice due to the very low through thickness conductivity. A metal matrix composite, presumably aluminum, is a better choice. For this to work, the K1100 needs to be woven into a fabric, then aluminum infiltrated. K800 fiber may be an acceptable alternative fiber. It is cheaper, has lower modulus, and a higher CTE.

- Carbon/Carbon will need to be impregnated with either a resin or metal matrix to improve the through thickness tensile strength. Through thickness conductivity is generally sufficient due to the structure of C/C. ROI has an extensive data base on C/C and other high conductivity graphite materials which we purchased. An advantage of C/C is that the layup, and hence directional properties, is determined at the perform stage. We have looked at a 4:1 K1100 C/C and determined that a substantial thermal advantage is there. CTE will vary substantially in both directions. However, that may be acceptable.

- ThermalGraph 8000 panel volume fraction is apparently very reproducible. TG8000 is very much like C/C in that it requires resin or metal impregnation to improve the through thickness tensile properties. Unlike C/C, it is extremely directional in its in-plane thermal and mechanical properties as a result of the manufacturing method to produce it. If we wanted more quasi-isotropic in-plane properties, one method would be to machine thin panels (on the order of 10 to 20 mils) and laminate them together. This would waste a lot of material, however. Laminates of cross plied K1100/cyanate unidirectional tape on a core of TG8000 may improve overall thermal plane properties. A few plies of K1100 would improve the transverse conductivity and CTE properties while retaining the very good longitudinal thermal conductivity of the TG8000. TG8000 is one of the few products able to attain very high (80% of more) volume fractions of K1100.

- TC1050 thermal conductivity has been confirmed at ROI. However, the test really only shows point-to-point conductivity within the board and not the actual conductivity of a real thermal plane. There are two possible high thermal resistance locations, the faceskin to pyrolytic graphite interface and the pyrolytic graphite to frame interface. We will need measurements on real thermal planes to see if the point thermal conductivity can be translated into performance.

THERMAL PERFORMANCE

Two dimensional SINDA finite difference analyses of various thermal plane configurations were completed using the Motor Power Switch (MPS) board chip watt densities. The figures show the temperature profile plotted versus x-y location in the board (6.53" by 6.53"), and assume a 90 mil thick thermal plane unless otherwise noted. A uniform cold sink of 60°C was assumed for along one edge as a boundary condition. Figure 3 shows that the BeO baseline performance results in a maximum temperature of 86°C. A quasi-isotropic layup of K1100, as shown in Figure 4, will lower the maximum temperature three degrees to 83°C. Note that a unidirectional layup of K1100, Figure 5, will actually increase the maximum temperature on the board. This is a result of poor transverse conductivity (cyanate ester resin system assumed) in the board. ThermalGraph 8000

a 4:1 layup of K1100 carbon/carbon, Figures 6 and 7, have sufficient transverse conductivity to distribute the heat over the board and still lower the maximum temperature to 75°C and 74°C, respectively. Finally, a thermal plane of 60 mils TC1050, Figure 8, results in a dramatically lower maximum temperature of 68°C. Note, however, that the properties of TC1050 are largely unknown, and therefore judgment must be reserved.

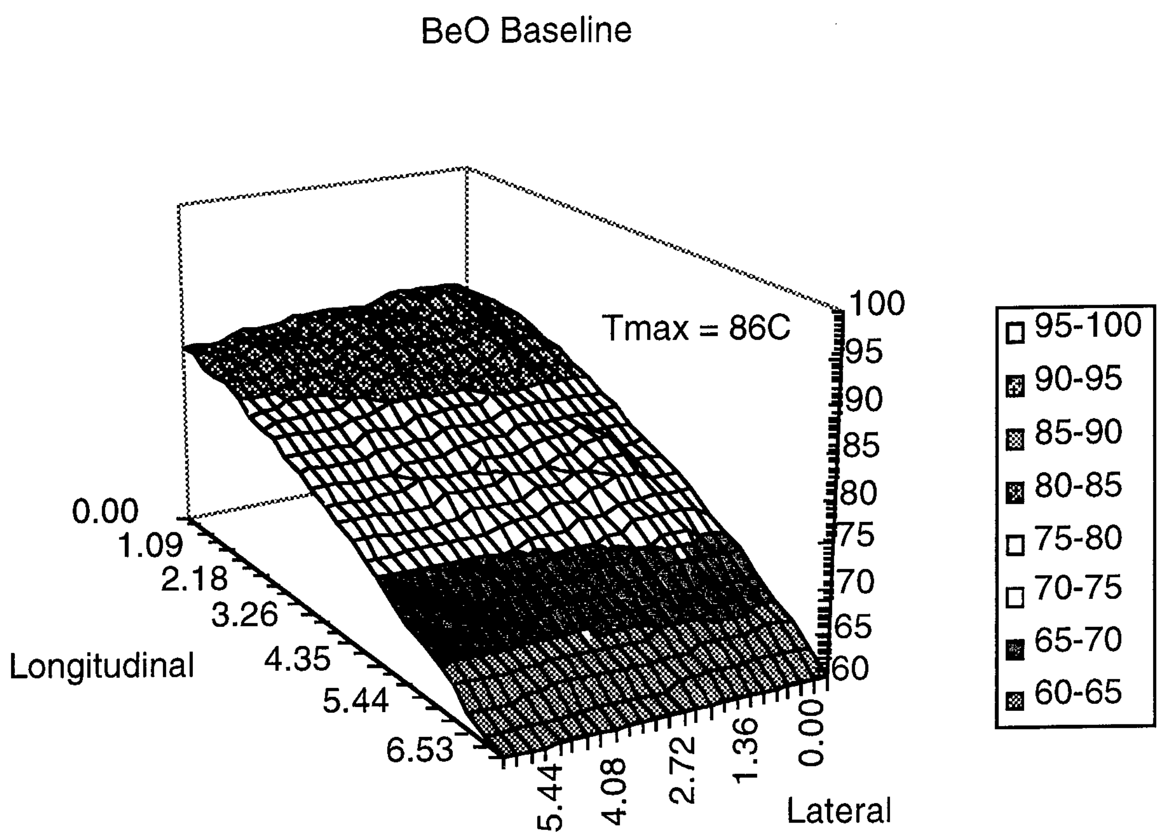

Figure 3 BeO baseline thermal plane performance.

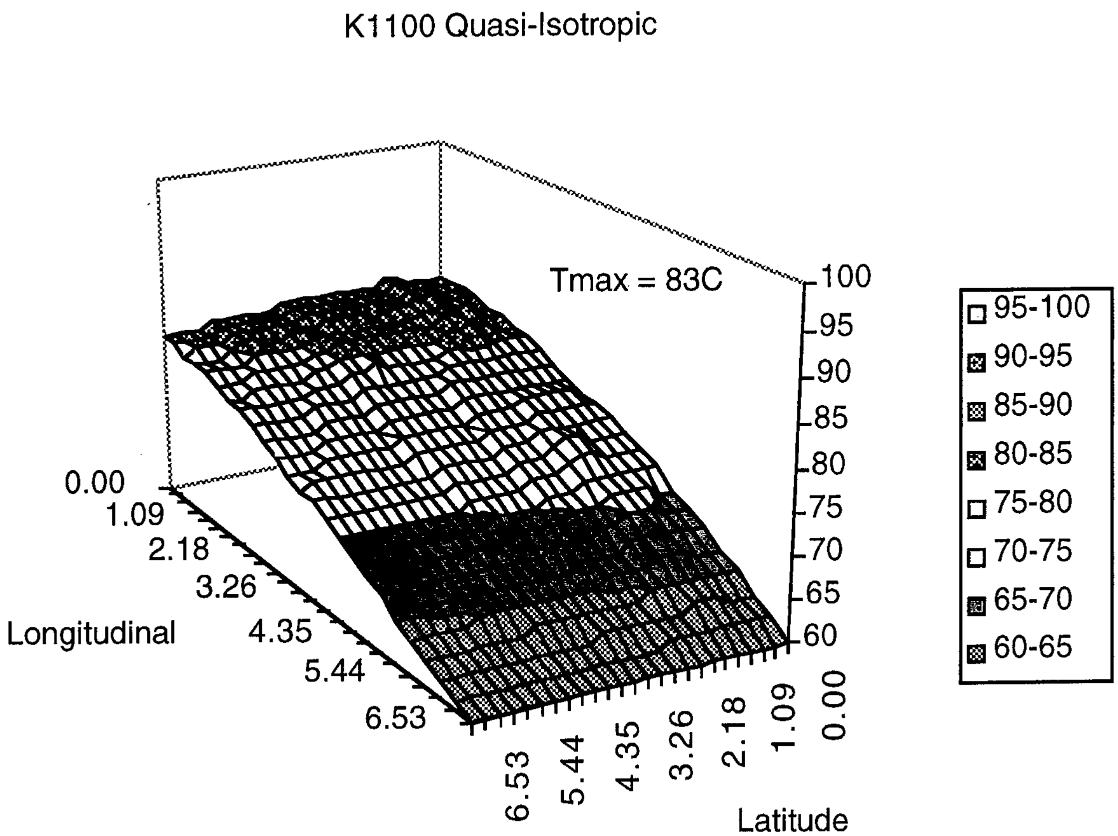

Figure 4 K1100 quasi-isotropic thermal plane performance.

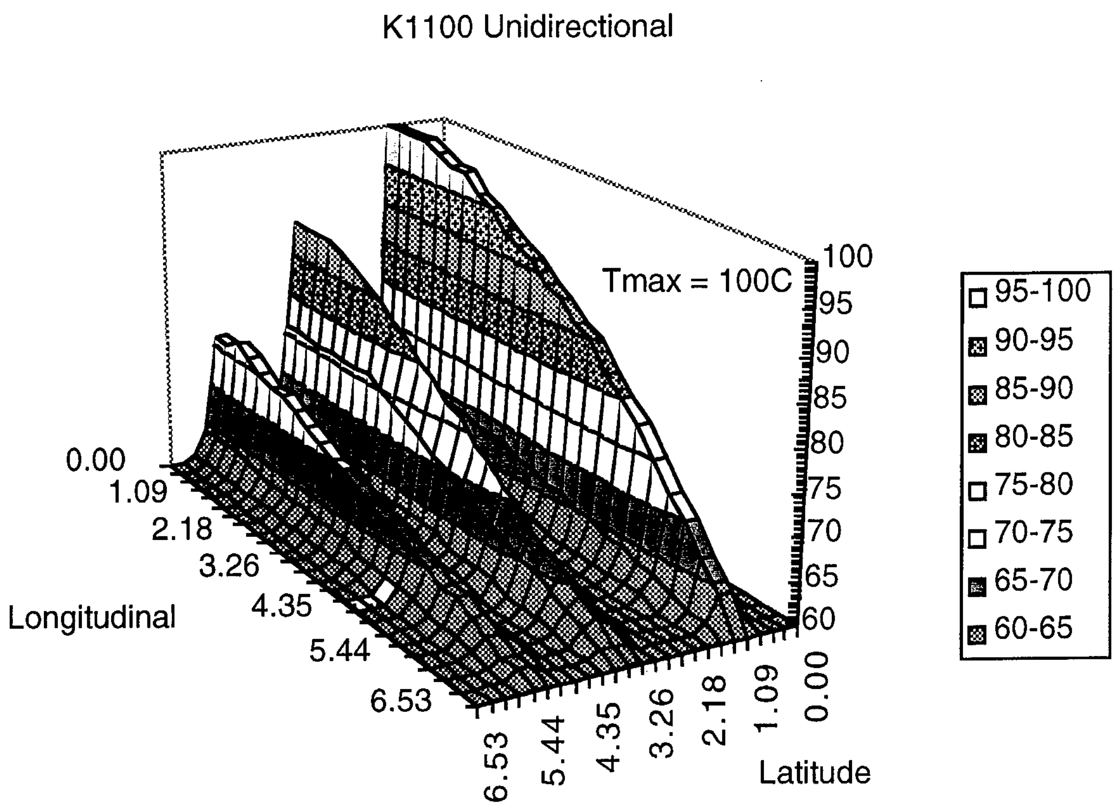

Figure 5 K1100 unidirectional tape thermal plane performance.

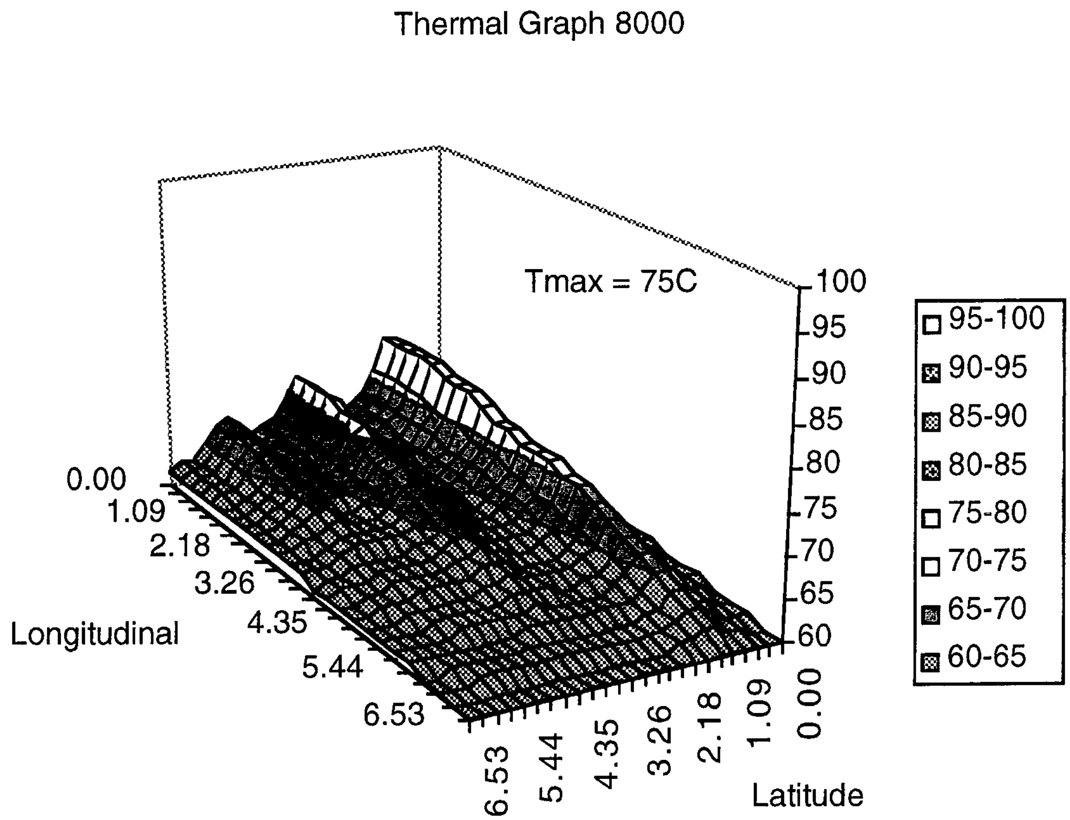

Figure 6 ThermalGraph 8000 thermal plane performance.

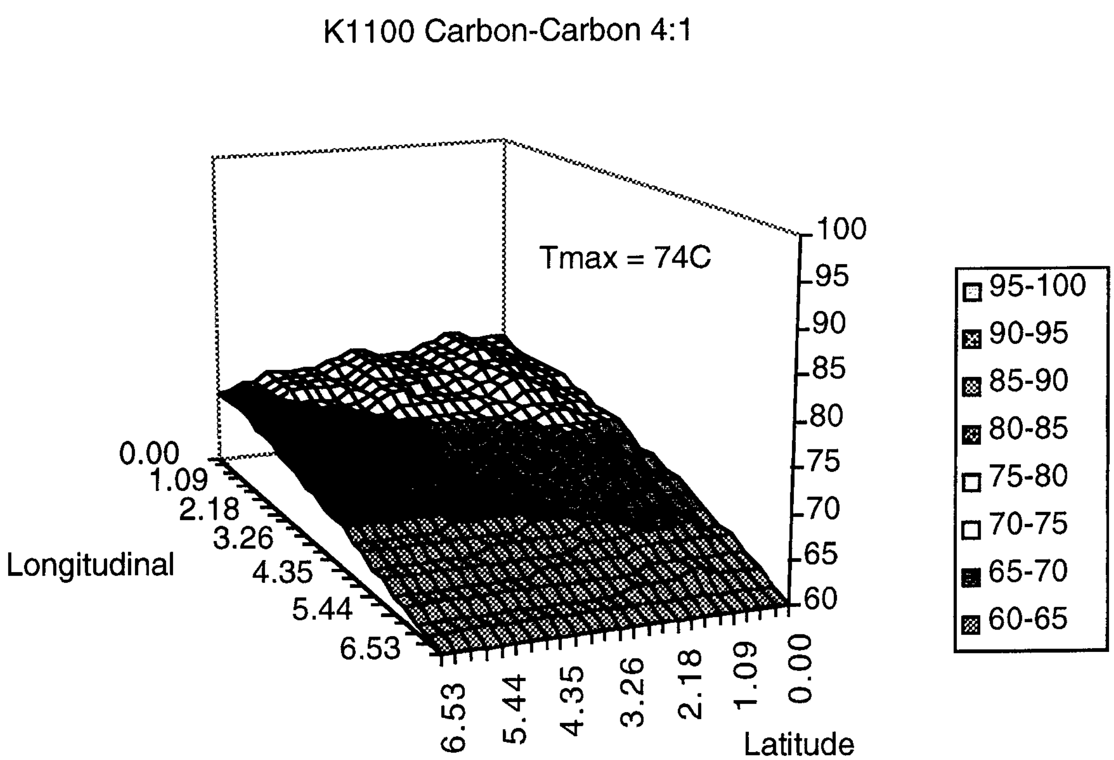

Figure 7 K1100 C/C 4:1 thermal plane performance.

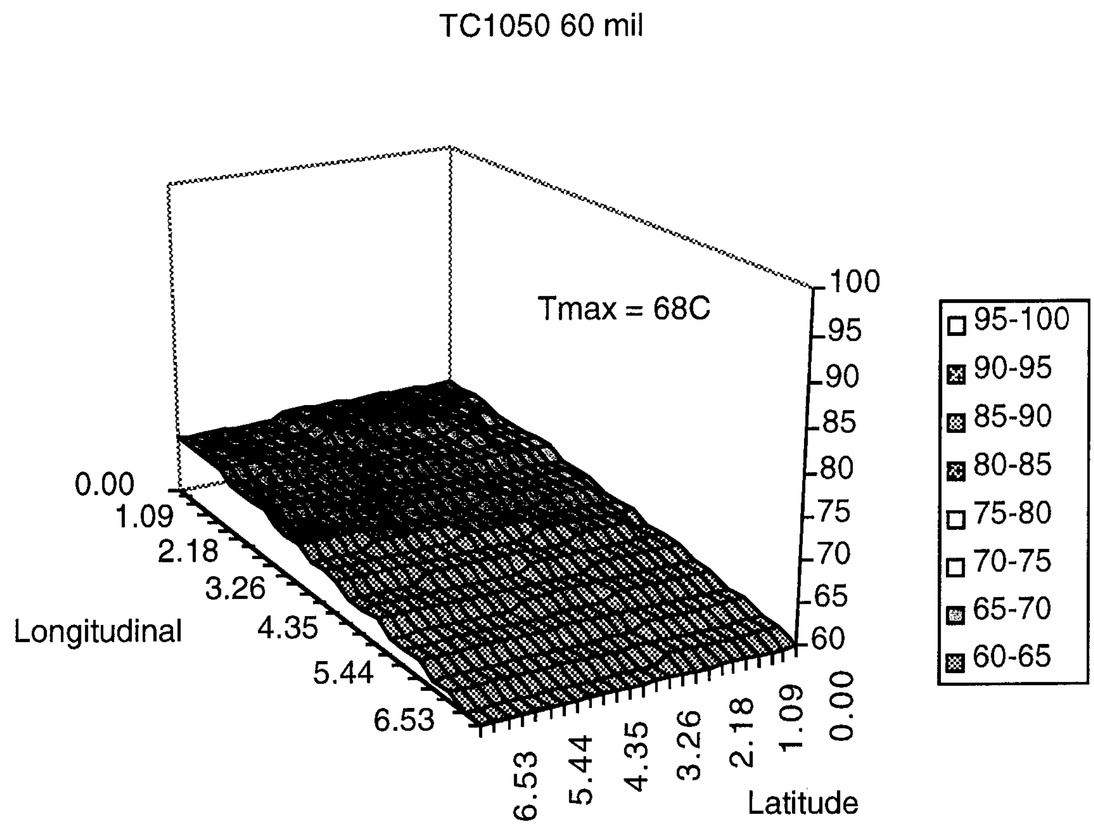

Figure 8 TC1050 60 mil thermal plane performance.

MECHANICAL PERFORMANCE

The mechanical performance of printed wiring board/thermal planes using ThermalGraph as the thermal core with varying cross plied layers of K1100 tape is documented in the Table 3 below. TG8000 is 80 v/o ThermalGraph infiltrated with epoxy. Likewise, TG6000 is 60 v/o ThermalGraph infiltrated with epoxy. The number of K1100 cross plies is inferred through thickness. The properties of the ThermalGraph were calculated using the principles of micromechanics. Notice that so long as the thermal plane consists substantially of unidirectional fibers, the longitudinal CTE remains unacceptably low. Furthermore, the maximum thermal stress occurs in the crossply K1100 fibers and is indicated in the chart. The compression strength of K1100 is under 40 ksi, so that all of these designs would fail mechanically. This analysis suggests two courses of action: (a) consider TC1050 as a thermal plane, since the mechanical action of the skins is decoupled from the thermal performance of the pyrolytic graphite core, and/or (b) maximize the thermal conductivity of the core (e.g. TG8000 only) and constrain the printed wiring board itself to 6 ppm/K with K1100 (or other graphite) plies. Option (b) implies, however, that PWB and thermal plane must now be joined using a thermally conductive compliant adhesive.

Table 3 Thermal Plane Performance

PWB/Thermal Plane/PWB	Long. CTE	Tran. CTE	Long. K (not inc. PWB)	Tran. K (not inc. PWB)	Max Stress (-140°K ΔT)
PWB/K1100/TG8000/K1100/PWB (63/5/80/5/63 mil) epoxy infiltrated/2.5° wind	-0.03	8.3	682.	103.	-106 ksi
PWB/K1100/TG6000/K1100/PWB (63/5/80/5/63 mil) epoxy infiltrated/2.5° wind	0.5	8.8	512.	91.	-113 ksi
PWB/K1100/TG8000/K1100/PWB (63/10/70/10/63 mil) epoxy infiltrated/2.5° wind	0.3	4.9	597.	152.	-68 ksi
PWB/K1100/TG6000/K1100/PWB (63/10/70/10/63 mil) epoxy infiltrated/2.5° wind	1.0	5.2	448.	142.	-72 ksi
PWB/K1100/TG6000/K1100/PWB (63/20/50/20/63 mil) epoxy infiltrated/2.5° wind	2.0	2.4	321.	243.	-40 ksi

TASK 2 TRAYS

REQUIREMENTS DEFINITION

The requirements/goals for trays include thermal conductivity, manufacturability, stiffness and strength, minimum mass, EMI shielding and radiation shielding. The trays have traditionally never been analyzed for CTE performance. Radiation shielding requirements may dominate the design. However, we have not been funded under this program to investigate radiation shielding.

Candidate compliant adhesives and tray materials are being reviewed.

TASK 3 EQUIPMENT PANELS

The finite element code Pro/Mechanica Structure and Thermal has been purchased and installed on a company workstation. The equipment panel task can now begin the modeling effort.

APPENDIX A MATERIAL PROPERTIES

Table A-1. K1100 Metal Matrix Systems[1,2]

Property	K1100/6063 Aluminum	K1100/6063 Aluminum
Vendor	MMCC	Amercom
Fiber Volume	37%	37%
Long. Thermal Cond.(W/m-K)	284	271
Tran. Thermal Cond.(W/m-K)	274	264
Longitudinal CTE (ppm/K)	3.3	2.7
Transverse CTE(ppm/K)	3.3	3.0
Tensile Strength (ksi)	56.6	42.5
Tensile Modulus (Msi)	25.2	25.7
Compressive Strength (ksi)	21.2	19.6
Compressive Modulus (Msi)	32.4	30.8
Density (g/cm^3)		

Table A-2. C/C Systems[1,3]

Property	C/C	C/C	C/C	C/C	C/C
Vendor	C-CAT	Aerotherm	BP-Hitco	BFGoodrich	FMI
Fiber Volume					
Long. Thermal Cond.(W/m-K)	204.9	278.2	217.7	322.4	259.9
Tran. Thermal Cond.(W/m-K)	199.6	280.0	214.2	325.0	256.4
Z Thermal Cond.(W/m-K)	6.6	41.7	7.2	20.9	55.4
Longitudinal CTE (ppm/K)	-1.0	-0.6	-1.1	-1.0	-0.9
Transverse CTE(ppm/K)	-1.0	-1.0	-1.0	-1.0	-1.2
Long. Tensile Strength (ksi)	53.0	11.3	9.6	7.2	11.4
Tran. Tensile Strength (ksi)	48.0	9.9	37.4	12.3	6.2
Z Tensile Strength (ksi)	0.36	0.97	0.21	0.88	0.99
Long. Tensile Modulus(Msi)	24.6	23.2	23.0	26.9	20.0
Tran. Tensile Modulus (Msi)	25.2	20.8	21.6	25.5	20.7
Compressive Strength (ksi)	15.5	11.6	11.4	12.5	10.8
Compressive Modulus (Msi)	23.5	31.0	22.5	26.5	16.0
Density (g/cm^3)	1.23	1.60	1.55	1.81	1.72

Table A-3. More BF Goodrich C/C Systems[4]

Property	BFG HT2 K1100 2D 4:1	BFG HT2 K1100 2D 1:1	BFG HT2 P120 2D 4:1	BFG HT2 P120 2D 1:1	BFG HT2 K321 2D 4:1	BFG HT2 K321 2D 1:1	BFG 3D Isotropic
Vendor							
Fiber Volume							
Long. Thermal Cond.(W/m-K)	553	360	380	250	368	201	266
Tran. Thermal Cond.(W/m-K)	153	358	111	250	97	200	188
Z Thermal Cond.(W/m-K)	48	52	38	45	45	32	244
Longitudinal CTE (ppm/K)	-1.5	-0.075	-1.5	-1.0	-1.5	-1.0	0.72
Transverse CTE(ppm/K)	-0.05	-0.075	-0.5	-0.75	-0.5	-0.75	0.78
Z CTE(ppm/K)	5 - 7	5 - 7	5 - 7	5 - 7	5 - 7	5 - 7	1.09
Long. Tensile Strength (ksi)	55	35	45	30	55	46	4.6
Tran. Tensile Strength (ksi)	13	na	8	na	14	na	
Long. Tensile Modulus (Msi)	47	32	43	28	53	37	2.0
Tran. Tensile Modulus (Msi)	13	na	10	na	9	na	
Long. Compressive Strength (ksi)	20	14	26	na	18	19	11.8
Tran. Compressive Strength (ksi)	na	na	na	na	6	na	
Long. Compressive Modulus (Msi)	47	na	33	na	34	26	1.5
Tran. Compressive Modulus (Msi)	na	na	na	na	9	na	
Density (g/cm^3)							

Table A-4. ThermalGraph Panel Systems[3]

Property	SRG Panel ± 2.5° Wind	SRG Panel ±11° Wind	SRG Panel ± 30° Wind	SRG Panel ± 45° Wind
Vendor	Amoco	Amoco	Amoco	Amoco
Fiber Volume	63%	63%	57%	58%
Long. Thermal Cond.(W/m-K)	576	505	491	337
Tran. Thermal Cond.(W/m-K)	30	39	113	238
Z Thermal Cond.(W/m-K)	~20 - 40[5]	~20 - 40[5]	~20 - 40[5]	~20 - 40[5]
Longitudinal CTE (ppm/K)	-1.2	-3.7	-3.5	-1.1
Transverse CTE(ppm/K)	42.9	31.7	13.6	-1.3
Z CTE(ppm/K)	~8-10[5]	~8-10[5]	~8-10[5]	~8-10[5]
Long. Tensile Strength (ksi)	64.0	43.4	23.1	11.0
Tran. Tensile Strength (ksi)	0.5	1.2	3.3	7.8
Long. Tensile Modulus (Msi)	69.0	50.6	22.4	9.0
Tran. Tensile Modulus (Msi)	0.7	0.8	1.2	4.5
Long. Compressive Strength (ksi)	33.1	25.0	16.8	11.4
Tran. Compressive Strength (ksi)	3.2	6.9	7.9	11.2
Long. Compressive Modulus (Msi)	68.6	55.6	18.9	7.1
Tran. Compressive Modulus (Msi)	1.2	0.9	1.8	3.3
Density (g/cm^3)				

Table A-5. ThermalGraph Woven Fabric Systems

Property	EWC 300/resin[1]	EWC 500/resin[1]	EWC 600/resin[1]
Vendor			
Fiber Volume	63%	78%	47.5%
Long. Thermal Cond.(W/m-K)	80	147	111
Tran. Thermal Cond.(W/m-K)			
Z Thermal Cond.(W/m-K)			
Longitudinal CTE (ppm/K)			
Transverse CTE(ppm/K)			
Tensile Strength (ksi)			
Tensile Modulus (Msi)			
Compressive Strength (ksi)			
Compressive Modulus (Msi)			
Density (g/cm^3)			

Table A-6. TC1050 Systems

Property	TC1050/ aluminum[6]	TC1050/ copper[2]	TC1050/ SiC/Al[2]	TC1050/ pitch fiber/Al[2]	TC1050/ pitch fiber/polymer[2]
Vendor					
Fiber Volume					
Long. Thermal Cond.(W/m-K)	1140	1142	1176	1020	1180
Tran. Thermal Cond.(W/m-K)	1140	1142	1176	1020	1180
Z Thermal Cond.(W/m-K)					
Longitudinal CTE (ppm/K)					
Transverse CTE(ppm/K)					
Tensile Strength (ksi)					
Tensile Modulus (Msi)					
Compressive Strength (ksi)					
Compressive Modulus (Msi)					
Density (g/cm^3)	2.52	4.45	2.95	2.30	2.13

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[1] W. C. Riley, "Development of High Thermal Conductivity Graphite Fiber Composites for Thermal Management," ROI Technology Update, 26 February, 1996.

[2] R. Bacon, M. K. Towne, W. C. Riley, "Processing Technology for Passive Thermal Management Composites using High Thermal Conductivity Graphite Fibers, Task 1. Metal Matrix Composites (MMC) for Electronic Applications, Final Report," CARDIVNSWC-TR-95/004, 1 June 1995.

[3] G. W. Ward, W. C. Riley, B. J. Sullivan, "Processing Technology for Passive Thermal Management Composites using High Thermal Conductivity Graphite Fibers, Task 2. Ceramic Matrix Composites (CMCs) for electronic Applications - Feasibility Study, Task 3. Ceramic Matrix Composites (CMCs) using High Thermal Conductivity Graphite Fibers" CARDIVNSWC-TR-95/032, 31 October 1995.

[4] W. Shih, "Advanced Carbon Composites for Electronic Applications," BFGoodrich Aerospace Division, Advanced Materials for Electronics Technical Conference, Washington, DC, 17-18 January 1996.

[5] "High Thermal Conductivity Pitch Based Graphite Fibers," Amoco Performance Products, Inc., product brochure.

[6] T. Kassin, "Encapsulated TPG Graphite TC1050 Material System," k Technology Corporation, Advanced Materials for Electronics Technical Conference, Washington, DC, 17-18 January 1996.